

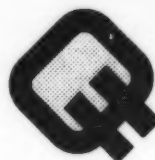
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PRESSURE TUBE THICKNESS COMPENSATION FOR THE SLAR GAP MEASUREMENT SYSTEM

Report No. 91-75-K

J.H. Sedo, Engineer
Advanced Systems Technology Section
Metallurgical Research Department

ABSTRACT

An approach is described for improving the thickness compensation scheme of the SLAR gap measurement system. The increase in accuracy and reliability of the system is most noticeable with near concentric fuel channel conditions, precisely when the results must be most accurate for the garter spring unloading procedure to be effective.

The new compensation signal is based on an estimate of the EC thickness response and not just on raw UT thickness measurements. The estimate is obtained by modeling the interaction of the EC probe and the pressure tube thickness variations as a linear time/space invariant system. It is shown how a general damped L_2 deconvolution procedure can suggest parametric function forms for the impulse response of the system, and how a constrained L_2 deconvolution procedure can determine the optimum parameters.

The complete procedure is simplified to conform to SLAR constraints and full details for its implementation are given.

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EXECUTIVE SUMMARY

The SLAR system uses rotary gap measurement scans to determine how best to unload garter springs in preparation for their relocation. In certain fuel channels, the results from these scans have been consistently inaccurate, to the point of preventing any meaningful determination of where the spring is pinched.

The cause of the problem is similar to an issue that was examined for the CIGAR gap measurement system. The SLAR EC probe, while sensitive to gap variations, is also sensitive to pressure tube thickness variations. In an effort to remove this influence the EC signal is currently compensated by point UT thickness measurements. However, the highly focused UT probe and the more broadly focused EC probe sense the thickness variations differently. This difference is not readily apparent when the system is used in tubes which, like the calibration tube, contain a smooth single lobe thickness variation around the circumference, but in tubes with multiple lobes or distorted single lobes, the UT and EC responses differ and the compensation procedure breaks down.

More accurate and robust compensation can be provided by using an estimate of the EC thickness response instead of just the raw UT measurements. The estimate is provided by a linear time/space invariant system model of the interaction of the EC

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probe and the thickness variations. The work here parallels much of what was done for CIGAR but also extends that work by showing how the characteristic parameters of the system model may be determined directly by a constrained L_2 deconvolution procedure.

As part of an effort to simplify the new procedure for the SLAR system, the model parameters for 10 probes were determined. It was shown that, except for a single gain parameter, all probes could be characterized by common parameter values without adverse consequences. The remaining gain parameter must be determined for each probe in a manner similar to current SLAR calibration procedures.

The procedure was further simplified by ignoring any axial thickness variations within the field of the EC probe and reducing the model to one dimension. This greatly reduced the amount of UT data required for a single rotary gap scan and yet still produced quite acceptable results in a variety of laboratory samples. The best improvement was a change in error from ± 1.88 mm (indicated gap variation over 360 degrees) at concentric conditions with the old compensation procedure to an error of ± 0.41 mm with the new procedure.

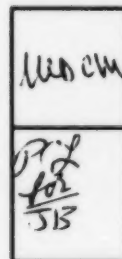


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To: J. Erven
Supervising Project Engineer
SLAR Project
Retube Engineering Dept.
In-service Nuclear Projects

**PRESSURE TUBE THICKNESS COMPENSATION
FOR THE SLAR GAP MEASUREMENT SYSTEM**

1.0 BACKGROUND

The SLAR (Spacer Location and Relocation) equipment contains a system to measure the spacing or gap between the pressure tube and calandria tube. One of its major functions is to perform a rotary scan in the vicinity of a garter spring to determine how best to jack the pressure tube and unload the spacer. Inaccurate results from this scan increase both the time and number of jacking cycles required to unload and move the spacer since the procedure becomes more dependent on trial and error.

The gap system is based on an eddy current probe which responds to changes in gap, pressure tube thickness and liftoff (probe to tube ID spacing)/1/. The liftoff response may be eliminated by operating the EC instrument at a frequency which separates this response from the others by approximately 90° in phase. Placing the liftoff response on the X-channel of the instrument then leaves the Y-channel free from this influence. The remainder of the report will refer to the Y-channel output of the properly adjusted EC instrument as the EC signal.

To compensate for the thickness influence in the EC signal, an ultrasonic transducer is mounted near the pickup coil and connected to a Novascope thickness measurement instrument. Presently the UT data, multiplied by a calibrated gain factor, is used directly in the gap equation to correct the EC data on a point by point

basis. The result is supposed to be proportional to gap alone but recent tests at AECL-SPEL have shown that this is not always the case.

2.0 THE PROBLEM

During rotary gap scans, pressure tube thickness variations large enough to significantly affect the EC gap probe are normally encountered. In many tubes these variations have a smooth single lobe shape because of a slight offset between the centers of the ID and OD surfaces. Straightforward compensation of the EC thickness response using UT measurements has generally worked fairly well for this type of variation. In fact, the calibration tube is specified to have a wall thickness distribution of this type. However, for tubes with multiple thickness lobes or distorted single lobes, the raw UT data does not provide adequate compensation.

The problem is evident in the top graph of Figure 10. Not only is the shape of the EC thickness response smoother than the UT compensating signal, but it is also much smaller in magnitude. The UT compensation gain used for this figure was the same as was used to generate the rather good results in the single lobe calibration tube (top graph of Figure 5). The reason for this poor result is that the UT probe is spot focused and can follow the actual thickness variations quite well whereas the EC probe with its broad field has difficulty responding to the more closely spaced or sharply changing variations.

One way to improve the compensation procedure is to obtain a better estimate of the EC response to wall thickness variations.

3.0 A LINEAR SYSTEMS APPROACH

Current assumptions about the EC gap probe allow the interaction of the probe with the pressure tube thickness variations to be modeled as a linear time/space invariant system. These assumptions are:

- (i) The EC thickness response is linear over the entire range of interest;
- (ii) The EC thickness response is independent of position, gap or any other variable.

As a result, the principle of superposition applies and allows the system to be characterized by its response to a fundamental input, the unit delta function (essentially a spike of unit area). Knowledge of this response is then sufficient to calculate the system output due to any input. This is done by considering the input as an integration of scaled and shifted delta functions and calculating the system response as an integration of scaled and shifted delta function responses. The procedure is formally expressed as the well-known convolution integral, shown here for the two dimensional system under consideration.

$$\tilde{y}(x, \theta) = \int_{-\pi}^{\pi} \int_{-\infty}^{\infty} u(\lambda, \theta) h(x - \lambda, \theta - \theta) d\lambda d\theta \quad (1)$$

$\tilde{y}(x, \theta)$ = modeled EC thickness response

$u(x, \theta)$ = pressure tube thickness as measured by the UT system

$h(x, \theta)$ = impulse or delta function response of the EC probe

x = axial position

θ = rotary position

Note that $\tilde{y}$, u and h are periodic in the rotary direction.

The task of determining the impulse response is greatly simplified if it can be considered to be separable along the position axes.

$$h(x, \theta) = h_A(x) h_R(\theta) \quad (2)$$

There is some basis for this assumption as it is thought that the physical mechanism primarily responsible for the nature of the impulse response is different along each axis/2/. This separation allows h_A and h_R to be considered as impulse responses of different one dimensional systems and therefore, allows them to be determined by more straightforward procedures.

4.0 GENERAL DECONVOLUTION TO A HIGH ORDER MODEL

The impulse response of a linear time invariant system may be determined from measured input and output values using a deconvolution process. The problem is generally ill-conditioned and ill-posed, and as a result, has inspired many techniques in an attempt to obtain a meaningful solution. A popular technique is outlined here to provide a foundation for the one finally used for SLAR (Section 6). The selection of appropriate input and output data for the deconvolution process is described in Appendix A.

The problem formulation is made easier if the convolution of sampled or discrete data is viewed as a matrix operation. Appendix B shows how the discrete form of the convolution integral can be expressed as

$$\tilde{y} = Uh \quad (3)$$

and how it may be efficiently computed for both the axial and rotary cases. Note that substituting the measured output y for the modeled output $\tilde{y}$ in equation 3 and solving for h generally yields noise due to the ill-conditioned nature of the problem, minor departures from modeling assumptions, and noise in u and y .

Another way of approaching the problem is to use the modeled output in some cost function which when minimized yields the best estimate of $\mathbf{h}$. A common measure of performance for a model is the L_2 norm of the modeling error.

$$Q = \|\mathbf{y} - \tilde{\mathbf{y}}\|^2 = \|\mathbf{y} - \mathbf{U}\mathbf{h}\|^2 \quad (4)$$

Q is a quadratic function of $\mathbf{h}$ in n space ($n = \#$ of pts in $\mathbf{h}$) and as such can be minimized very efficiently by the iterative conjugate gradient method/3,4/. When this is done with typical data, obtained as specified in Appendix A, an important observation can be made. The value of Q approaches its minimum value with relatively few iterations after which further reduction is accomplished by causing $\mathbf{h}$ to oscillate wildly in an attempt to compensate for deviations from linear model assumptions or noise and errors in data measurements. As a result, the iterative process may be stopped long before a final minima is reached yet still achieve an excellent fit between $\tilde{\mathbf{y}}$ and $\mathbf{y}$. However, the resulting oscillatory $\mathbf{h}$ is not a good representation of the data independent system characteristics.

What is really needed is some means of finding the best acceptable $\mathbf{h}$ that minimizes the L_2 norm of the modeling error. The procedure should allow a trade-off between imposing desirable characteristics on $\mathbf{h}$ and the resulting increase in modeling error caused by these demands. This can easily be done for the expectation that $\mathbf{h}$ should be smooth. The new cost function

$$Q = \|\mathbf{y} - \mathbf{U}\mathbf{h}\|^2 + \|\lambda\mathbf{h}\|^2 \quad (5)$$

includes a damping parameter λ that allows one to perform this trade-off. Figure 2 shows the damped and undamped estimates of $\mathbf{h}$ for the axial data in Figure 1. Notice that the increase in smoothness of $\mathbf{h}$ was achieved with very little increase

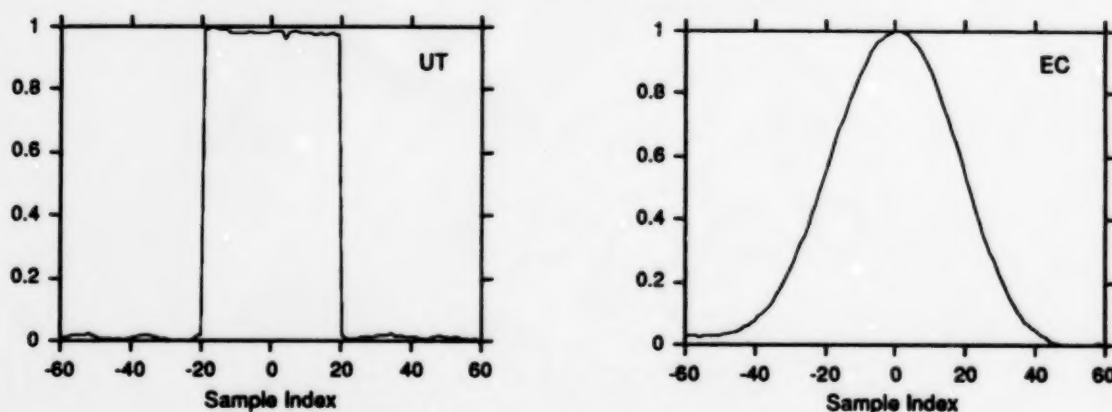


Fig 1. Normalized and centered deconvolution data. The baseline UT data extends beyond what is shown here and forms the $\mathbf{U}$ matrix as described in Appendix B. The EC data is the observed output of the system and forms the $\mathbf{y}$ vector.

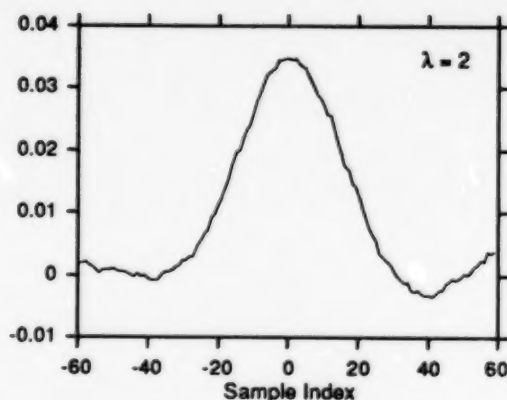
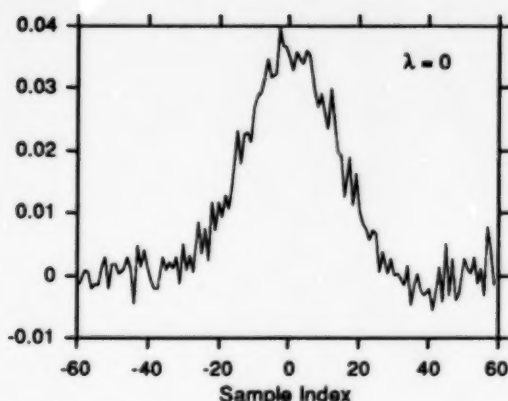


Fig 2. Estimates of $\mathbf{h}$ produced by minimizing equation 5 with 40 iterations of a conjugate gradient algorithm. The model output ($\mathbf{U}\mathbf{h}$), produced by the undamped estimate ($\lambda = 0$), fits the observed EC data slightly better than the output produced by the damped estimate (MSE = 4.4E-7 as opposed to 9.4E-6). However, in both cases the error is too small to be seen with the scale used in Figure 1.

in model error. Similar damped results were achieved in a previous report on the CIGAR gap probe, but by using a different and somewhat more heuristic procedure^{2/}.

5.0 REDUCTION TO A LOW ORDER PARAMETRIC MODEL

If $\mathbf{h}$ is to represent the underlying physical behaviour of the system, then it is reasonable to expect that it could be modeled with only a limited number of degrees of freedom. This agrees with the previous expectation that a good estimate of $\mathbf{h}$ should be smooth. Thus far, $\mathbf{h}$ has been formulated using an independent parameter for each point in the estimate. The cost function in equation 5 penalizes excessive use of these numerous degrees of freedom and as a result, produces a solution that could be represented by fewer parameters.

The selection of a model structure for $\mathbf{h}$ with the minimum number of parameters necessary to achieve an adequate fit between $\mathbf{y}$ and $\tilde{\mathbf{y}}$ may be guided by the shape of high order estimates of $\mathbf{h}$ as well as physical insights into the system being modeled. Previous work for the CIGAR gap measurement system used these considerations to arrive at the following function forms for $\mathbf{h}_A$ and $\mathbf{h}_R$:

$$\mathbf{h}_A = A \exp\left[\frac{-(\mathbf{x}-\mathbf{pk})^2}{w^2}\right] + B \quad (6)$$

$$\mathbf{h}_R = A \left[\alpha \sin^2(\theta - \mathbf{pk}) + (1 - \alpha \cos(\theta - \mathbf{pk}))^2 \right]^{-1.5} + B \quad (7)$$

These functions may be fitted to the high order estimates of h_A and h_R for either the CIGAR or SLAR systems. This technique was used with reasonable success for CIGAR to determine the best parameter values for each probe/2/. For the SLAR project, the need to evaluate the variation of the parameters between probes made a more direct and repeatable method desirable.

6.0 DIRECT DECONVOLUTION TO A LOW ORDER PARAMETRIC MODEL

The two step deconvolution procedure outlined in section 5 is useful for determining the parametric function forms, but it is not the most robust way of estimating the optimum parameter values. The weakness is the indirect use of the performance criteria $\|y - \tilde{y}\|^2$ when determining the parameter values. Adjusting the parameters to minimize the error between the parametric model of h and the high order estimate of h does not guarantee that the resultant values minimize $\|y - \tilde{y}\|^2$. It would be better to constrain the estimate of h in the original deconvolution problem to conform to the desired parametric function.

This can be done with one of a number of algorithms developed to solve the general non-linear least squares problem:

$$\text{Minimize } E^2(c) = \|y - f(c, x)\|^2 \quad (8)$$

The standard use for these algorithms is to fit an arbitrary function of m parameters to some data y collected as a function of x . Generally, for the algorithms to converge to a well-defined global minima, the parameter vector c should be of minimum dimension m , with the elements as independent as possible, and be initialized at a good guess c_0 . A particularly robust algorithm, referred to as the BFGS method, was used for the deconvolution problem outlined below/5,6/.

Equation 8 is a generalized form of the deconvolution problem described in equation 4. The previous formulation required the model output $\tilde{y}$ to depend on a large number of unknowns ($h_i, i=1, n$) in a linear fashion. Here, this restriction is relaxed so that the model output may depend in a nonlinear fashion on, what should be, a smaller set of unknowns ($c_i, i=1, m$).

For the axial case equation 8 becomes

$$\text{Minimize } E^2(c) = \|y - U h_A(c, x)\|^2 \quad (9)$$

where h_A is defined in equation 6
and $c = (A, B, pk, w)$.

and for the rotary case

$$\text{Minimize } E^2(c) = \|y - Uh_R(c, \theta)\|^2 \quad (10)$$

where h_R is defined in equation 7
where $c = (A, B, pk, \alpha)$

Efficient and robust minimization of E^2 by the BFGS algorithm requires the computation of the Jacobian of the fitting function. Although the software used to perform the minimization can estimate the Jacobian by using a numerical differentiation process, the formulation of the convolution operation as a matrix multiplication makes it easy to perform the calculation explicitly. For the axial case

$$\text{Jacob } f(c, x) = [U \partial h_A / \partial A, U \partial h_A / \partial B, U \partial h_A / \partial pk, U \partial h_A / \partial \alpha] \quad (11)$$

and for the rotary case a similar expression applies. Note that the columns of the Jacobian are expressed as the convolution matrix multiplied by a vector. This rather time consuming operation can be accelerated by using the FFT in the same way as described for the computation of Uh in Appendix A.

7.0 SLAR IMPLEMENTATION

The optimum parameters for the impulse responses h_A and h_R were determined for 10 SLAR probes by the non-linear least squares procedure outlined in the previous

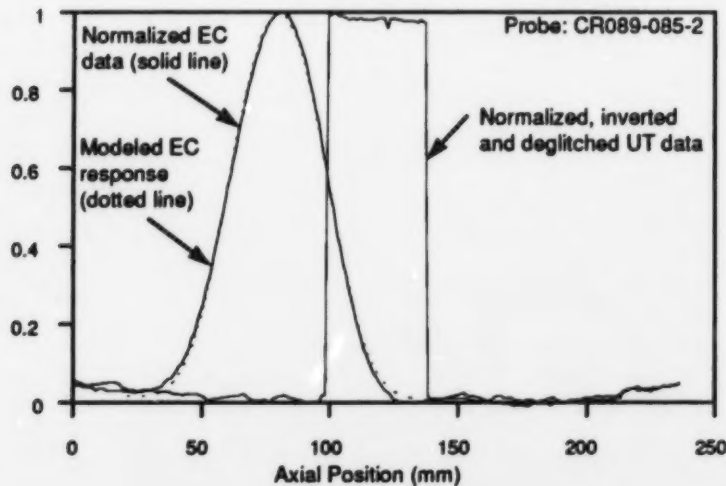


Fig 3. Typical SLAR axial deconvolution results.
Data obtained as described in Appendix A.
Significant model parameters are shown in Table 1.

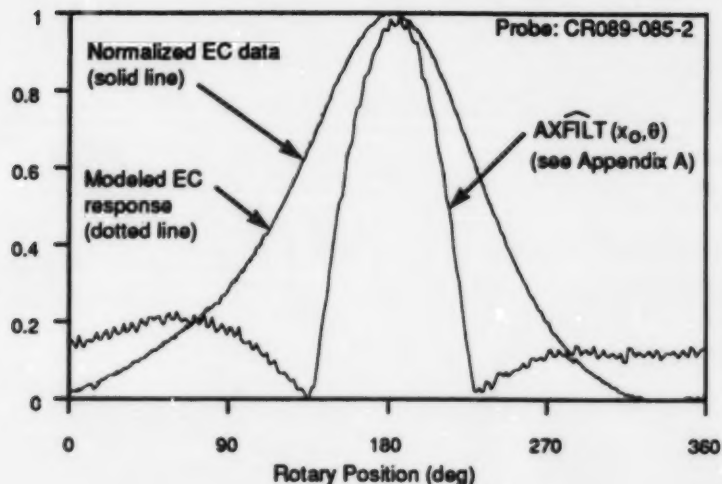


Fig 4. Typical SLAR rotary deconvolution results.
Data obtained as described in Appendix A.
Significant model parameters are shown in Table 1.

section. Appropriate input and output data were selected from scans of a machined calibration standard as described in Appendix A. The results for a typical probe are shown in Figures 3 and 4. Note that constraining the impulse responses to be of the forms shown in equations 6 and 7 has not resulted in significant modeling error. Similar results were obtained for all 10 probes and have been summarized in a table of significant parameters.

The B parameters for both h_A and h_R are absent from Table 1 because their effect is overridden in the SLAR gap equation. An absolute gap reference is obtained by forcing the average of all computed gap values in any 360° cross-section to equal the nominal design value of 8.5 mm. As a result, the B parameters are only included in the impulse response functions to account for the arbitrary offsets that the input and output data may contain and to ensure that the best estimates are obtained for the other parameters.

The A parameters are also absent from Table 1. At present, the gap equation uses a thickness correction factor to scale the raw UT data and obtain an appropriate thickness correction signal. This factor is determined from a scan in a calibration facility that is part of the SLAR delivery system. This must be done on the system because of the number of system factors that can affect the sensitivity of the EC probe/instrument combination. This practice should remain when the raw UT data is replaced by the estimated EC thickness response in the gap equation. Therefore, the magnitude of the impulse response may be set to some convenient yet consistent value and the role of the gain parameters left to the thickness correction factor in the gap equation.

The SLAR delivery system is rather limited in its capability for movement and as a result, the collection of UT data over the full extent of the impulse response function would take an unacceptable amount of time. Therefore, it has been decided to assume that the pressure tube wall thickness is axially uniform over the extent of h_A (nominally 94 mm wide to 1% levels). This is not a bad assumption for most tubes since they are drawn during manufacture, but there is room for error especially where local grinding has been performed to reduce the wall thickness or where there is some rotational shift of the thickness lobe along the tube. The assumption allows h_A to be set to unity and drastically reduces the data collection requirements for single rotary gap scans. As a result, the pk and w parameters of h_A are not used in the SLAR gap measurement procedure and are presented in Table 1 for interest only.

The procedure used to determine the parameters of h_R makes use of the full form of h_A to extract appropriate input and output data (see Appendix A) and therefore, is both complicated and time-consuming in terms of data collection and computation. It would be desirable if this procedure could be carried out in the laboratory and common values for the remaining significant h_R parameters (pk and α) used for all SLAR gap probes.

Presently it is assumed that the UT and EC data are rotationally aligned (ie. $pk = 0$). The rotary pk values listed for the 10 probes in Table 1 are close to zero, but some variation exists, probably due to a combination of manufacturing differences and experimental error. Therefore, if a common value for pk is to be used, then some small error between the actual EC thickness response and the modeled EC thickness response, dependent on the individual probe in use, must be accepted. An attempt will be made to evaluate this error, but first the issue of a common value must be addressed. The mean and standard deviation of the rotary pk values listed in Table 1 are 0.3° and 0.7° , respectively. While one could use the mean value for the tested probes as the common value, the design value of 0° is more appealing. The standard deviation is so large in comparison with the difference between these two values that the use of the design value is entirely justified.

No design value exists for the α parameter and so the best estimate of a common value is the mean of the α values listed in Table 1. The modeling error incurred by using the mean was, for each of the probes tested, comparable or somewhat less than that incurred by using a value of 0° for pk .

This modeling error can be put in perspective by examining a variety of experiments performed to estimate a confidence interval for α . Results show that, although repetitive scans with a constant experimental set-up produce fairly consistent α values ($\sigma=0.002$, computed from 4 scans using probe CR089-085-2), small changes in the experimental set-up can produce more significant variations. For example, varying the phase angle (adjusted before each scan to null out the liftoff influence) by $\pm 1^\circ$ produced α values for the 085-2 probe that varied by a total of

0.01. Furthermore, introducing a gap variation of only 0.15 mm between the pressure tube calibration standard and its calandria tube produced α values for the same probe that varied by a total of 0.02, depending on the orientation of the point of maximum gap with respect to the machined thickness variation. These variations in the calculated α value for the one probe were due to relatively minor changes in the experimental set-up, but they are almost as large as those between any of the probes in Table 1 (constant experimental set-up).

These observations support the use of a common value for the α parameter since the error in doing so is not significantly greater than that from other sources. Since the modeling error incurred by assuming the design value of 0° for p_k is comparable, this simplification is also supported.

Significant h_A & h_R Parameters				
	Rotary		Axial	
SLAR Probe #	Shape α	Offset p_k (deg)	Shape w (mm)	Offset p_k (mm)
CR089-085-1	.2538	-.71	20.59	-53.68
CR089-085-2	.2459	-.58	23.29	-51.64
CR089-088-1	.2624	.57	22.47	-51.78
CR089-088-2	.2561	.40	21.55	-52.70
CR089-094-1	.2464	-.59	22.03	-51.50
CR089-094-2	.2478	1.50	21.47	-51.92
CR089-100-1	.2519	.88	22.72	-51.81
CR089-100-2	.2602	-.59	21.15	-51.76
CR089-106-1	.2595	1.09	22.53	-51.94
CR089-106-2	.2630	-.01	21.33	-51.66
μ	.2547	0.30	21.91	-52.04
σ	.006	0.7	0.8	0.6

Table 1. Significant parameters of a random selection of SLAR gap probes. The rotary and axial offsets are wrt the focal spot of the embedded UT transducer. The negative direction of the axial offset is towards the EC send coil.

The end result is that the impulse response for SLAR is greatly simplified over the general case.

$$\mathbf{h} = \mathbf{h}_R (A=K, B=0, pk=0, \alpha = \bar{\alpha}) \quad (12)$$

where $\mathbf{h}_R$ is given in equation 7

$\bar{\alpha} = 0.255$ from Table 1

K is set so that $\sum_{i=1}^n h_i = 1$

Appendix C shows in detail how equation 12 should be used in the SLAR gap measurement system.

8.0 COMPENSATION PERFORMANCE

Rotary gap scans were performed in a number of pressure tube samples to compare the performance of the old and new compensation methods. For all tests, a calandria tube was fitted to the pressure tube samples in a concentric configuration in order to easily evaluate the compensation error. Note that a calandria tube must be present as it affects the impulse response of the EC probe. As specified, the SLAR gap equation parameters were calibrated on a pressure tube with a reasonably well behaved single lobe thickness variation. Figures 5 to 10 contrast the results obtained from the two compensation methods in a number of pressure tube samples.

The new method works as well or better than the old method in all cases. The most significant improvement was achieved with the data from a multiple lobe tube (Figure 10). The old method indicated a 360° gap variation of 1.88 mm whereas the new method indicated a much smaller 0.41 mm variation.

9.0 CONCLUSIONS

- (1) The results from SLAR rotary gap scans can be improved by compensating for the effect of pressure tube thickness variations with an estimate of the EC probe's thickness response rather than with the raw UT thickness measurements.
- (2) An estimate of the EC thickness response may be produced from the UT data by modeling the interaction of the EC probe and the thickness variations as a linear time/space invariant system.
- (3) The impulse response of this model may be considered to be separable along the position axes and may be represented by different low order parametric

functions in each direction.

- (4) The optimum parameter values for a typical SLAR gap probe may be determined in a robust and repeatable fashion by using a deconvolution process which constrains the impulse response to be a parametric function of the desired form.
- (5) Despite the SLAR implementation constraints that made it necessary to ignore the axial dimension of the problem and to use some common parameter values for all probes, a substantial improvement in compensation performance was achieved.

10.0 RECOMMENDATIONS

- (1) The new compensation procedure may be incorporated in the SLAR system to improve gap measurement precision (see Appendix C for details).
- (2) The CIGAR gap measurement system uses a similar thickness compensation scheme but incorporates the two step process, outlined in section 5, to determine the characteristic parameters of the probe. It would be advantageous to update this to the more robust and repeatable one step procedure outlined in section 6.

ACKNOWLEDGEMENT

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Approved by:

Prepared by:

P. C. Zink

John H. Sedo

J. Brown
J. Brown
Manager
Metallurgical Research Dept

J.H. Sedo
Engineer
Advanced Systems Technology

JHS:SEHG

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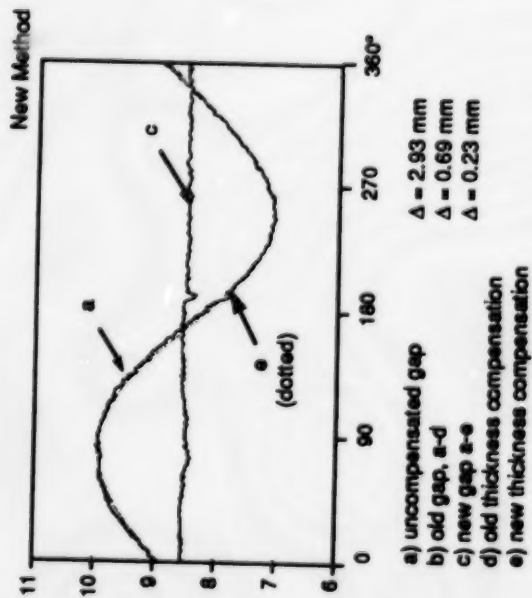
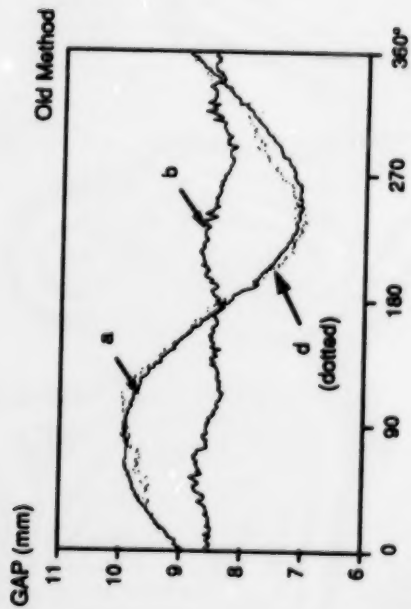


Fig 5. Concentric SLAR gap scans of tube 8c (calibration tube for compensation gain).
 Δ thickness of tube = 0.134 mm

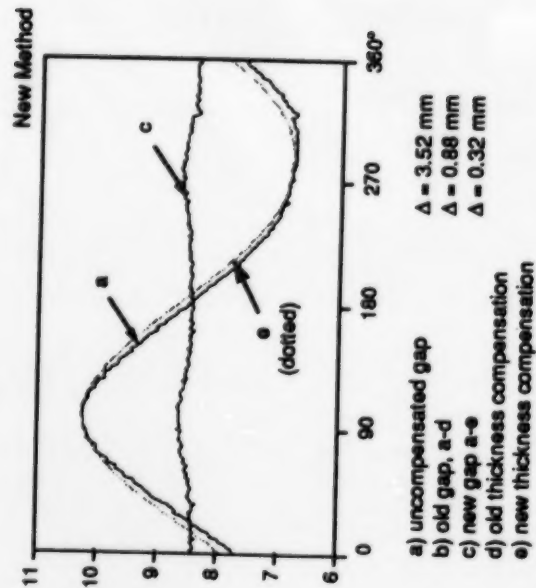
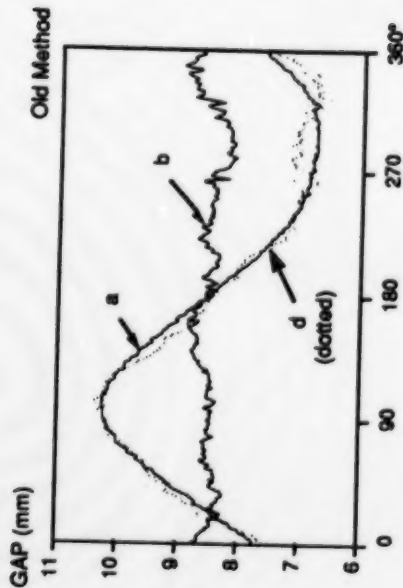
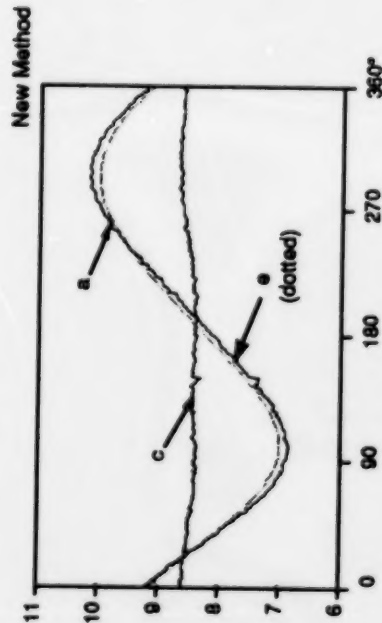
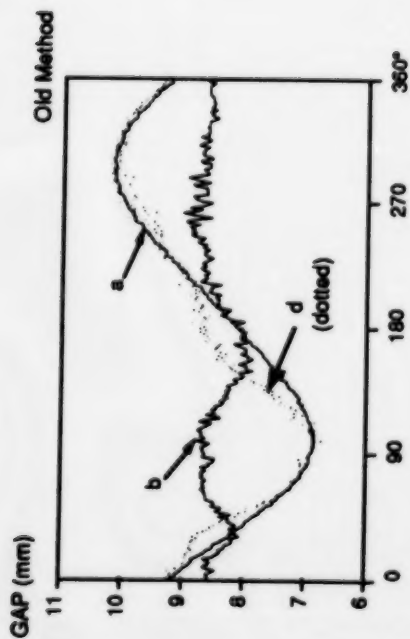
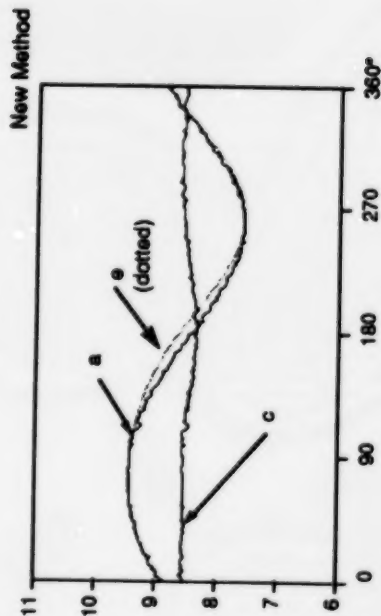
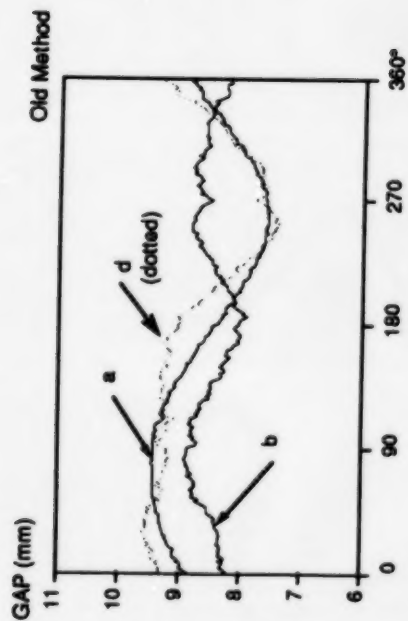


Fig 6. Concentric SLAR gap scans of tube 6b.
 Δ thickness of tube = 0.169 mm



- a) uncompensated gap $\Delta = 3.31$ mm
- b) old gap, a-d $\Delta = 1.16$ mm
- c) new gap, a-e $\Delta = 0.39$ mm
- d) old thickness compensation
- e) new thickness compensation

Fig 7. Concentric gap SLAR scans of tube 7c.
 Δ thickness of tube = 0.158 mm



- a) uncompensated gap $\Delta = 1.89$ mm
- b) old gap, a-d $\Delta = 1.02$ mm
- c) new gap, a-e $\Delta = 0.33$ mm
- d) old thickness compensation
- e) new thickness compensation

Fig 8. Concentric SLAR gap scans of tube 2b.
 Δ thickness of tube = 0.097 mm

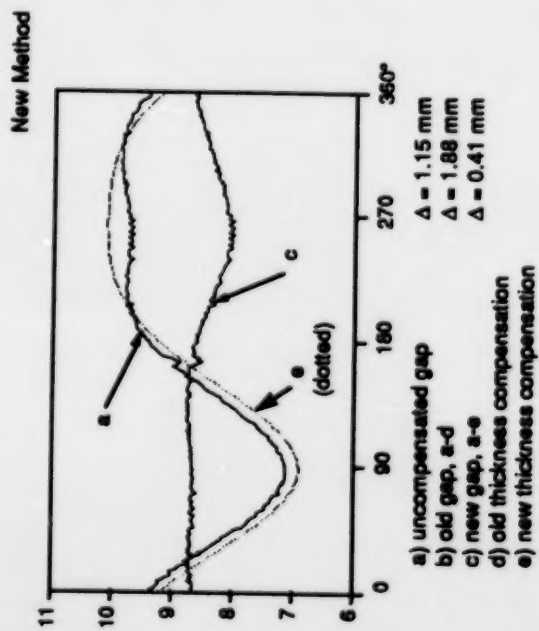
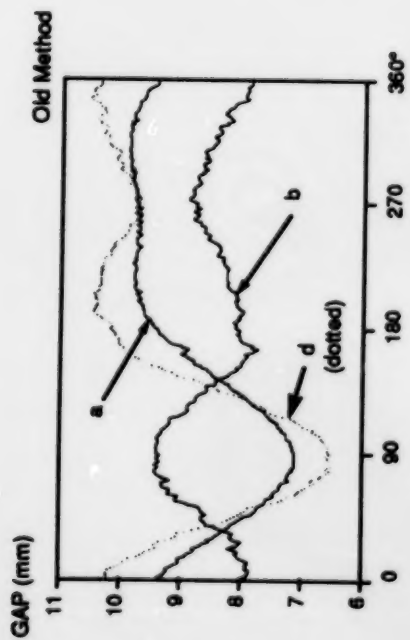


Fig 9. Concentric gap SLAR scans of tube 0m.
 Δ thickness of tube = 0.180 mm

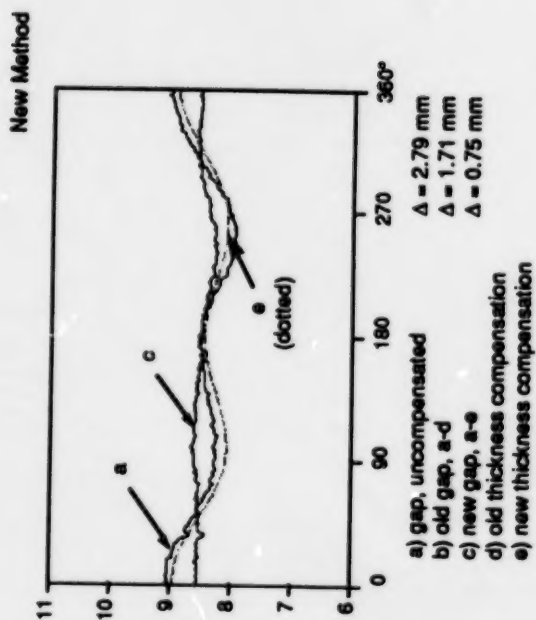
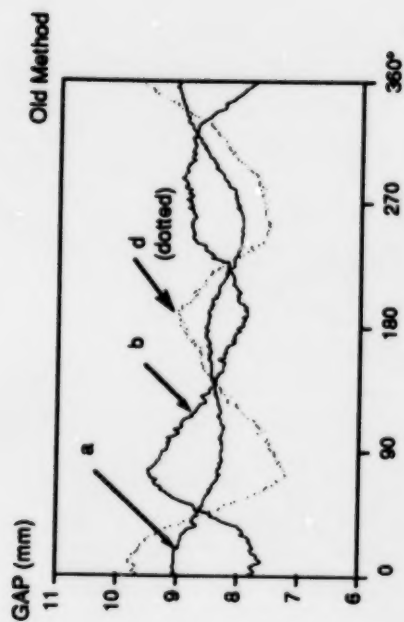


Fig 10. Concentric SLAR gap scans of tube 4t.
 Δ thickness of tube = 0.116 mm

APPENDIX A

Selection of Data for Deconvolution

The selection of input data for the purpose of identifying the impulse response of a linear time/space invariant system should take into account several issues:

- i) The input should provide a stimulus to the system that has a significant frequency content over the range to which the system is capable of responding.
- ii) The input should produce an output which is significantly above the background noise.
- iii) The input should not violate the linear assumptions of the model by being too extreme.
- iv) Care should be taken that the measured output is due only to the measured input and not other influences.

With these guidelines in mind, the machined thickness variation shown in Figure A1 was chosen as an appropriate input. This calibration standard was placed in a calandria tube and the gap held as uniform as possible. Concentricity was verified by drilling four 1.7 mm holes spaced 90° apart in the calandria tube, both above and below the thickness variation, and measuring the gap with an electronic dial gauge. Variations in the readings were less than 0.03 mm in either section.

The calibration standard was scanned with a section of the SLAR tool body containing the EC gap probe, UT thickness transducer and any metallic fittings that would interact with the field of the EC probe. The UT instrument was adjusted for the velocity of sound in the Zr 2.5 wt%Nb pressure tube (4715 m/s) but not calibrated to read correct absolute values. As a result, the UT thickness data contains an arbitrary yet constant offset. The EC instrument was operated at 3 kHz (the recommended operating frequency of the gap probe /1/) and adjusted to place the signal

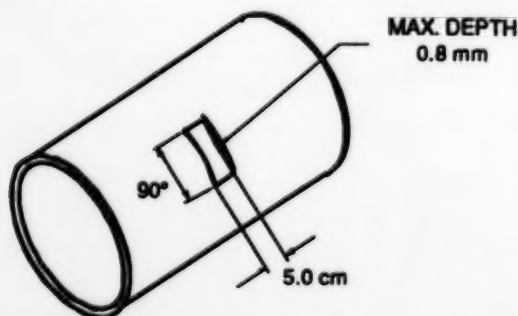


Figure A1. Calibration standard used to generate deconvolution data (Zr 2.5 wt%Nb pressure tube).

from an increase in pickup coil to pressure tube spacing along the positive X-axis. As a result, the signal due to increasing gap occurred predominantly in the positive Y-direction. Figures A1 and A2 show the EC and UT data collected at an axial spacing of 5 mm and a rotational sample rate of 256 pts/360°. The UT data has been deglitched by an algorithm that utilizes a median filter to create a smoothed data set and then replaces any points that deviate excessively from this reference set by the corresponding smoothed data points.

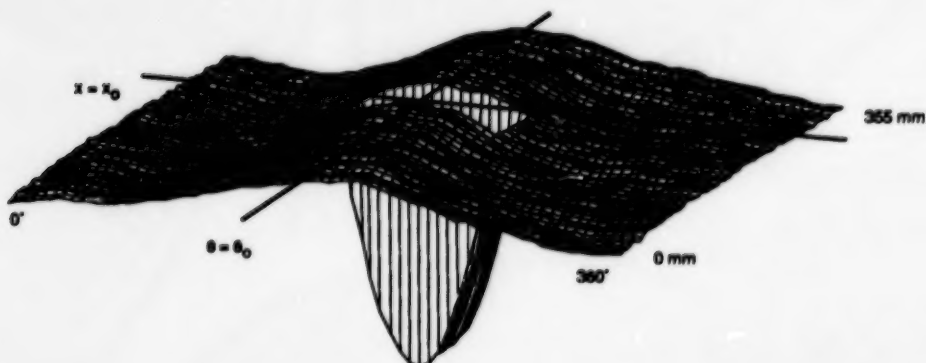


Figure A2. Typical SLAR UT thickness data (deglitched) obtained from the calibration standard shown in Figure A1. Axes θ_0 and x_0 pass through the peak of the machined thickness variation.

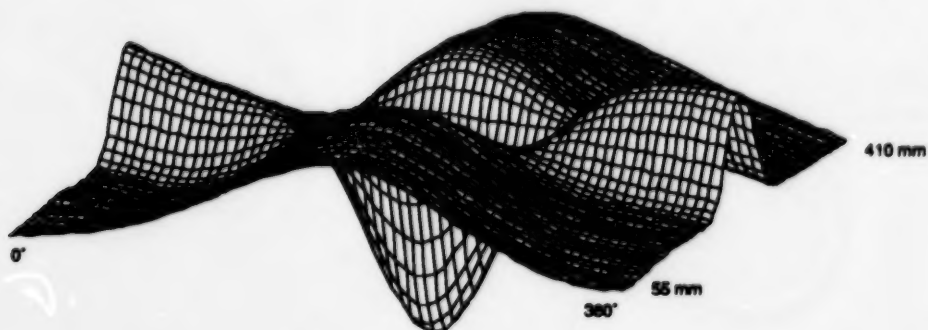


Figure A3. Typical SLAR EC data obtained during the same scan as the UT data shown in Figure A2. The data shown has been inverted and shifted axially to allow a good comparison between the responses of the EC and UT probes.

From the two dimensional data shown, one dimensional input and output data arrays must be selected to estimate $h_R(\theta)$ and $h_A(x)$. For clarity the discussion will use continuous data instead of the sampled data actually available. Since $h_R(\theta)$ is of more importance, $h_A(x)$ will be determined first with the use of some simplifying assumptions.

Axial Deconvolution

Assume

$$UT(x, \theta) = K_1(\theta) \widehat{UT}(x, \theta_0) + K_2(\theta) \quad (A.1)$$

where

$$\widehat{UT}(x, \theta_0) = \frac{UT(x, \theta_0) - \text{MIN}[UT(x, \theta_0)]}{\text{MAX}[UT(x, \theta_0)]}$$

and θ_0 is selected to pass through the peak of the machined thickness variation.

This expression states that axial profiles of $UT(x, \theta)$ differ only in gain and/or offset and as a result allows the two dimensional convolution integral to be reduced to one dimension.

This is shown below by starting with the 2D convolution integral and a separable EC probe impulse response, substituting equation A.1 for the UT data, and integrating where possible.

$$\begin{aligned} \widetilde{EC}(x, \theta) &= \int_{-\infty}^{\infty} \int_{-\pi}^{\pi} h_R(\theta - \vartheta) h_A(x - \lambda) UT(\lambda, \vartheta) d\vartheta d\lambda \\ &= \int_{-\pi}^{\pi} h_R(\theta - \vartheta) K_1(\vartheta) d\vartheta \int_{-\infty}^{\infty} h_A(x - \lambda) \widehat{UT}(\lambda, \theta_0) d\lambda + \int_{-\pi}^{\pi} h_R(\theta - \vartheta) K_2(\vartheta) d\vartheta \int_{-\infty}^{\infty} h_A(x - \lambda) d\lambda \\ &= G_A(\theta) \int_{-\infty}^{\infty} h_A(x - \lambda) \widehat{UT}(\lambda, \theta_0) d\lambda + C_A(\theta) \end{aligned} \quad (A.2)$$

where $G_A(\theta)$ and $C_A(\theta)$ are unknown functions of θ .

Equation 2 assumes that

$$\int_{-\infty}^{\infty} h_A(x - \lambda) d\lambda = L_1 < \infty$$

which is necessary for stability and quite reasonable for a real physical system. Concentrating on the EC thickness response along $\theta = \theta_o$, equation A.2 becomes

$$\widehat{EC}(x, \theta_o) = G_A(\theta_o) \int_{-\infty}^{\infty} h_A(x-\lambda) \widehat{UT}(\lambda, \theta_o) d\lambda + C_A(\theta_o) \quad (A.3)$$

Since the result of the axial convolution integral in equation A.3 differs from the estimated EC thickness response by an unknown gain and offset ($G_A(\theta_o)$ & $C_A(\theta_o)$), an equation of the same form may be used to describe an estimate of the normalized EC response $\widetilde{EC}(x, \theta_o)$.

$$\widetilde{EC}(x, \theta_o) = K_1 \int_{-\infty}^{\infty} h_A(x-\lambda) \widehat{UT}(\lambda, \theta_o) d\lambda + K_2 \quad (A.4)$$

where $\widetilde{EC}(x, \theta_o)$ is an estimate of $\widehat{EC}(x, \theta_o)$

$$\text{and } \widehat{EC}(x, \theta_o) = \frac{EC(x, \theta_o) - \text{MIN}[EC(x, \theta_o)]}{\text{MAX}[EC(x, \theta_o)]}$$

The unknown gain and offset (K_1 & K_2) in equation A.4 can be expressed as part of the axial impulse response instead of the model output.

$$\begin{aligned} \widetilde{EC}(x, \theta_o) &= \int_{-\infty}^{\infty} [k_1 h_A(x-\lambda) + k_2] \widehat{UT}(\lambda, \theta_o) d\lambda \\ &= \int_{-\infty}^{\infty} h_A(x-\lambda) \widehat{UT}(\lambda, \theta_o) d\lambda \end{aligned} \quad (A.5)$$

This equation assumes

$$\int_{-\infty}^{\infty} \widehat{UT}(\lambda, \theta_o) d\lambda = L_2 < \infty$$

which is not a problem if it is assumed that $\widehat{UT}(x, \theta_o) = 0$ outside the region of data collection.

From equation A.5, the one dimensional axial deconvolution problem may be for-

ulated:

Using a normalized input $\widehat{UT}(x, \theta_0)$ and normalized output $\widehat{EC}(x, \theta_0)$, determine an impulse response $h'_A(x)$ which differs from the desired impulse response $h_A(x)$ by an unknown gain and offset.

Since the gain and offset are not important (see Section 7), this procedure is satisfactory.

Rotational Deconvolution

The rotary problem may be reduced to one dimension by the use of a modified form of the axial impulse response $h'_A(x)$ determined previously. It is known that the desired axial impulse response $h_A(x)$ approaches zero as $x \rightarrow \pm \infty$ (ie. the probe is not sensitive to stimulus that is far away in the axial direction). Therefore, adjusting the offset of $h'_A(x)$ to produce a response $\hat{h}_A(x)$ that has the desired offset, creates a response that differs from $h_A(x)$ only by an unknown gain factor. Therefore, the full 2D convolution integral can be simplified as follows

$$\begin{aligned} \widetilde{EC}(x, \theta) &= \int_{-\pi}^{\pi} \int_{-\infty}^{\infty} h_R(\theta - \phi) h_A(x - \lambda) UT(\lambda, \phi) d\lambda d\phi \\ &= \int_{-\pi}^{\pi} h_R(\theta - \phi) \int_{-\infty}^{\infty} \frac{1}{k_1} \hat{h}_A(x - \lambda) UT(\lambda, \phi) d\lambda d\phi \\ &= \frac{1}{k_1} \int_{-\pi}^{\pi} h_R(\theta - \phi) AXFILT(x, \phi) d\phi \end{aligned} \quad (A.6)$$

$$\text{where } AXFILT(x, \theta) = \int_{-\infty}^{\infty} \hat{h}_A(x - \lambda) UT(\lambda, \theta) d\lambda$$

Considering only the EC thickness response estimate that passes through the peak of the machined thickness variation, equation A.6 becomes

$$\widehat{EC}(x_0, \theta) = \frac{1}{k_1} \int_{-\pi}^{\pi} h_R(\theta - \phi) AXFILT(x_0, \phi) d\phi \quad (A.7)$$

As for the axial case, an estimate for the normalized EC response in terms of a normalized input argument may be formulated using an expression of this form.

$$\widetilde{EC}(x_0, \theta) = K_3 \int_{-\pi}^{\pi} h_R(\theta - \phi) AXFILT(x_0, \phi) d\phi + K_4 \quad (A.8)$$

where $\widetilde{EC}$ is an estimate of $\widehat{EC}(x_0, \theta)$

$$\text{and } \widehat{EC}(x_0, \theta) = \frac{EC(x_0, \theta) - \text{MIN}[EC(x_0, \theta)]}{\text{MAX}[EC(x_0, \theta)]}$$

$$\text{and } AXFILT(x_0, \theta) = \frac{AXFILT(x_0, \theta) - \text{MIN}[AXFILT(x_0, \theta)]}{\text{MAX}[AXFILT(x_0, \theta)]}$$

Once again, the unknown gain and offset can be incorporated into the impulse response rather than on the convolution integral.

$$\begin{aligned} \widetilde{EC}(x_0, \theta) &= \int_{-\pi}^{\pi} [k_3 h_R(\theta - \phi) + k_4] AXFILT(x_0, \phi) d\phi \\ &= \int_{-\pi}^{\pi} h'_R(\theta - \phi) AXFILT(x_0, \phi) d\phi \end{aligned} \quad (A.9)$$

From equation A.9, the one dimensional rotary deconvolution problem can be formulated:

Using a normalized input $AXFILT(x_0, \theta)$ and normalized output $\widehat{EC}(x, \theta_0)$, determine an impulse response $h'_R(x)$ which differs from the desired impulse response $h_R(x)$ by an unknown gain and offset.

Again, since the gain and offset parameters are not important (see Section 7), this procedure is satisfactory.

APPENDIX B

Matrix Formulations of the Model Outputs

Axial Case

The axial deconvolution problem defined in Appendix A is aperiodic in nature and therefore, care must be taken to deal with end effects appropriately. The standard linear time invariant system description for the one dimensional sampled data case is

$$\tilde{y}[n] = \sum_{k=-\infty}^{\infty} u[k] h[n-k] \quad (B.1)$$

If it is assumed that the sampled input data $u[n]$ is zero outside of the measured region (ie. $u[n] = 0, |n| > N$) and that the impulse response $h[n]$ is of finite length (ie. $h[n] = 0, |n| > M, M < N$), then the model output $\tilde{y}[n]$ in equation (B.1) can be expressed as

$$\tilde{y}[n] = \sum_{k=-N}^N u[k] h[n-k] \quad (B.2)$$

Generally, $u[n]$ is not strictly zero for $|n| > N$ and as a result, the model output computed by equation B.2 may not be accurately compared with the real system output $y[n]$ over the full measured region, $|n| \leq N$. This can be demonstrated by setting $u[n] = 1, |n| \leq N$ and $h[n] = 1, |n| \leq M$ ($u[n] = h[n] = 0$ otherwise) and computing $\tilde{y}[n]$ according to equation B.2. Only the output samples produced when $|n| \leq N-M$ form a plateau and are therefore unaffected by the windowing of $u[n]$. As a result, this is the only region over which $\tilde{y}[n]$ and $y[n]$ should be compared.

Equation B.2 can also be expressed in matrix form.

$$\text{output of interest} \left\{ \begin{bmatrix} \tilde{y}[-N] \\ \vdots \\ \tilde{y}[-N+M] \\ \vdots \\ \tilde{y}[N-M] \\ \vdots \\ \tilde{y}[N] \end{bmatrix} \right\} = \begin{bmatrix} h[0] \dots h[-M] & & & & 0 \\ \vdots & \ddots & & & \\ h[M] \dots h[0] & \dots & h[-M] & & \\ & \ddots & \vdots & \ddots & \\ & & h[M] \dots h[0] & \dots & h[-M] \\ 0 & & & \ddots & \vdots \\ & & & h[M] \dots h[0] & \end{bmatrix} \begin{bmatrix} u[-N] \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ u[N] \end{bmatrix} \quad (B.3)$$

Since $h[n]$ is the unknown in the deconvolution problem, it is desirable to reformu-

late the output of interest in equation (B.3) to contain $h[n]$ as a single vector.

$$\begin{bmatrix} \tilde{y}[-N+M] \\ \vdots \\ \tilde{y}[N-M] \end{bmatrix} = \begin{bmatrix} u[-N+2M] \dots \dots u[-N] \\ \vdots \\ u[N] \dots \dots u[N-2M] \end{bmatrix} \begin{bmatrix} h[-M] \\ \vdots \\ h[M] \end{bmatrix} \quad (B.4)$$

$$\tilde{\mathbf{y}} = \mathbf{U}\mathbf{h}$$

The computation of $\mathbf{U}\mathbf{h}$, which can be quite time consuming, may be made more efficient by using the discrete convolution theorem and the FFT algorithm. For any two periodic sequences of period L , the following expression may be used.

$$s[n] \textcircled{L} r[n] = \text{IFFT} [\text{FFT}(s[n]) \cdot \text{FFT}(r[n])] \quad (B.5)$$

Care must be taken to respect the conditions for which equation (B.5) is true. First, note that the length of the two sequences must be the same and equal to a power of 2 in order to employ the FFT and IFFT routines. Second, note that the L point periodic convolution is specified and that this is different from the aperiodic convolution specified in equation (B.2). Therefore, sequences $u[n]$ and $h[n]$ must be zero padded to a length L , which must not only be a power of 2, but also sufficiently large so as to avoid the aliasing inherent in the periodic convolution from corrupting that portion of the result which is equal to the desired aperiodic convolution. If these conditions are met, then equation (B.5) will produce a sequence from which a portion may be extracted which will be equal to $\mathbf{U}\mathbf{h}$.

Rotary Case

The rotary deconvolution problem defined in Appendix A is periodic in nature and therefore, the computation of $\mathbf{U}\mathbf{h}$ is much more straightforward. Here $\mathbf{U}\mathbf{h}$ does equal $u[n] \textcircled{L} h[n]$ and may be efficiently computed using the full result of equation (B.5).

APPENDIX C

SLAR Implementation Details

Algorithm

The current SLAR GAP measurement system compensates the EC data by a simple measurement of wall thickness in the vicinity of the eddy current gap measurement sensor, with the equation

$$\text{gap}(\theta) = A \text{ EC}(\theta) + B (\text{UT}(\theta) - \text{UT}_0) + C$$

- A is the eddy current gain;
EC(θ) is the eddy current signal at angle θ ;
B is the wall thickness compensation gain;
UT(θ) is the ultrasonic wall thickness signal;
UT₀ is the ultrasonic thickness signal when the eddy current instrument is balanced;
C is the gap reference term, which causes the average gap value over 360° to be 8.5 mm.

For rotary gap reference scans and gap monitoring functions of SLAR (single gap and gap reference display), the wall thickness compensation term

$$B (\text{UT}(\theta) - \text{UT}_0)$$

is to be replaced by

$$B [\text{SUT}(\theta)]$$

where SUT(θ) is the smoothed UT wall thickness data and is calculated as shown in detail 5.

Details

- (1) All quantities that vary with rotary position (ie. EC, UT, f, gap and SUT) are represented by sequences of 360 points whose values are samples of the continuous variables obtained at a spacing of 1 degree.
- (2) Each sequence is indexed from 0 to 359. The rotary positions corresponding to these indices depend on the gap scan and the variable being considered.
- (3) As an example of typical data, consider a rotary gap scan from $\theta = -180^\circ$ to 179° . The following data is collected:

$$\begin{aligned} EC[n], n &= 0, 359 \\ UT[n] &= n = 0, 359 \end{aligned}$$

EC[0] and UT[0] correspond to the start of the scan ($\theta = -180^\circ$) where the EC instrument is balanced.

EC[359] and UT[359] correspond to the end of the scan ($\theta = 179^\circ$).

- (4) The form of the gap probe's impulse response function is

$$f[n] = K[\alpha^2 \sin^2(\theta_n) + (1 - \alpha \cos(\theta_n))^2]^{-3/2}$$

$\theta_n = n^\circ$, ie. $\theta_1 = 1^\circ$, $\theta_{-1} = -1^\circ$ etc.
 α = shape parameter. It is the same for all probes and is read from a parameter file.

$$K \text{ is set so that } \sum_{n=0}^{359} f[n] = 1$$

Note that $f[n]$ is the same for all scans. Because θ_n is the rotary position with respect to the gap probe pickup coil, it is not related to the starting position of the scan. Also, since $f[n]$ is symmetric about the pickup coil, the direction of the scan is not a concern.

- (5) The calculation of SUT[n] is performed as follows. Note that the UT data must be processed to be sure that it is valid and free of spikes. Low pass filtering should not be performed for this purpose as the filter will affect many data points in addition to the spike point.

$$SUT[n] = \sum_{m=0}^{359} (UT[m] - UT[0]) f[n-m], \quad n = 0, 359$$

- (6) The new gap equation is:

$$\text{gap}[n] = A EC[n] + B SUT[n] + C, \quad n = 0, 359$$

and the old gap equation is

$$\text{gap}[n] = A EC[n] + B UT[n] + C, \quad n = 0, 359$$

- (7) The B value in the wall thickness compensations term will be determined in the same way for both gap equations. The exact B value for any given probe will vary depending on whether the raw UT data is used (old equation) or the smoothed UT data is used (new equation).